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Possible observation of phase coexistence of the $\nu = 1/3$ fractional quantum Hall liquid and a solid

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We have measured the magnetoresistance of a very low density and an extremely high quality two-dimensional hole system. With increasing magnetic field applied perpendicularly to the sample we observe the sequence of insulating, $\nu = 1/3$ fractional quantum Hall liquid, and insulating phases. In both of the insulating phases in the vicinity of the $\nu = 1/3$ filling the magnetoresistance has an unexpected oscillatory behavior with the magnetic field. These oscillations are not of the Shubnikov-de Haas type and cannot be explained by spin effects. They are most likely the consequence of the formation of a new electronic phase which is intermediate between the correlated Hall liquid and a disorder pinned solid.

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Two-dimensionally confined charge carriers subjected to low temperatures (T) and high magnetic fields (B) display a multitude of phases. Among them are the series of well-known fractional quantum Hall (FQH) liquids [1] that terminate at high B in the high field insulating phase [2, 3]. There is mounting evidence [4] that the high field insulating phase is crystalline, often thought to be the Wigner solid (WS). The terminal FQH state, the liquid state with the lowest Landau level filling factor ν, is found to be the $\nu = 1/5$ in 2D electron [2] and the $\nu = 1/3$ in 2D hole systems [3]. Exception is the electron gas confined to an extremely narrow quantum well, a system for which the terminal FQH state is at $\nu = 1/3$ [5]. The difference between electron and hole samples is attributed to a profound change of the ground state energies of the FQH liquid and the WS that is due to Landau level mixing (LLM) [3]. LLM occurs when the separation between the single particle Landau levels is significantly less than the Coulomb interaction energy [6]. Since the effective mass m^* of the holes is about 5 times that of the electrons, holes have a smaller cyclotron energy $\hbar eB/m^*$ and therefore larger LLM. This enhanced LLM is thought to change the terminal FQH state.

Besides forming at high B field due to magnetic quenching of the kinetic energy, the WS can also form at $B = 0$ when the ratio r_s of the Coulomb and the Fermi energies is large [7]. The interaction parameter r_s can be expressed as $r_s = m^*e^2/(4\pi\epsilon\hbar^2\sqrt{\pi p})$, with p the areal density of the charges. It was thought that the WS, the ground state at large r_s, melts into the Fermi liquid around $r_s = 37$ [8]. However, exact diagonalization on small systems [9] with the Coulomb interaction included revealed that the melting of the WS into a Fermi liquid with decreasing r_s could occur in two steps resulting in the intriguing possibility of an intermediate phase between the WS and the Fermi liquid. Similarly, the possibility of an intermediate phase in charges confined to 2D has been shown for a system in which the Coulomb interaction is screened by a nearby metallic gate [10, 11] and for another system that exhibits a first order transition in the presence of non-uniformly distributed dopants when at least one of the phases is insulating [12]. The intermediate state could be liquid-crystal-like [11, 13] or an admixture of interpenetrating liquid and solid phases [9, 10, 11, 12].

In this Letter we report on a study of an extremely dilute two-dimensional hole (2DH) system with the density of $p = 0.98 \times 10^{10}$ cm^{-2}. At the 38 mK base temperature of our refrigerator the $\nu = 1/3$ FQH state is intercalated between two insulating phases. To our surprise, in both of these low and high field insulating phases we observe oscillations of the magnetoresistance with the B field, with a period of several mT. The observed oscillations may be the consequence of an intermediate phase of the 2DH system formed by coexisting FQH liquid and crystal phases. This intermediate phase is similar to the intermediate phase predicted in the $B = 0$ case, with the exception that the crystal coexists with the $\nu = 1/3$ FQH liquid, rather than the $B = 0$ Fermi liquid.

Our samples are grown on a (311)A GaAs substrate. The 2DH system is formed in a 30 nm wide GaAs/AlGaAs quantum well with Silicon dopants on both sides of the well. The mobility of the holes is $\mu = 0.36{\times}10^6$ cm^2/Vs at 38 mK. A recent cyclotron resonance experiment on a different piece from the same wafer reported $m^* = 0.37$ in units of free electron mass [14] which together with the very low density of $p = 0.98 \times 10^{10}$ cm^{-2} yields an exceptionally high $r_s = 30$. The ohmic contacts to the hole gas are made of InZn alloy. The size of the samples and the distance between the ohmic contacts are of the order of 1 mm and the voltage probes are on the side cut along the [$\bar{2}$33] direction. Transport measurements were carried out using the low frequency lock-in technique at an excitation current of 1 nA.

In Fig.1 we show the dependence on B of ρ_{xx} at four different temperatures and the Hall resistance at 38 mK.

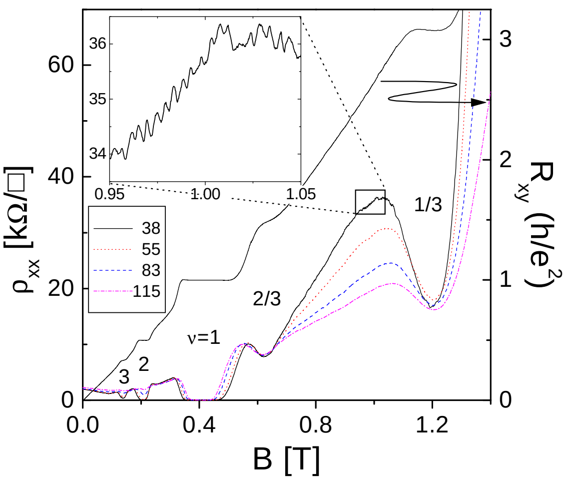

FIG. 1: The longitudinal resistivity ρ_{xx} and the Hall resistance R_{xy} at 38 mK. Legend shows the temperatures for ρ_{xx} in mK.

We observe fully developed integer quantum Hall states at $\nu = 1$, 2, and 3 and partially developed $\nu = 2/3$ and 1/3 FQH states. As we cool the sample, ρ_{xx} at $\nu = 1/3$ initially increases and only at the lowest temperatures $T < 60$ mK starts decreasing. In contrast, ρ_{xx} at $\nu = 2/3$ is decreasing with decreasing T in our measurement range. At $\nu < 1/3$ or equivalently for $B > 1.22$ T we observe the insulating phase that has been associated with the weakly pinned WS [3, 4]. While in 2DH samples of $p = 4 \times 10^{10}$ cm^{-2} at $\nu = 0.37$ a reentrant insulating phase with $\rho_{xx} > 300$ k$\Omega/\Box$ has been reported [3], in our sample we observe no clear reentrant behavior. The resistance between $1/3 < \nu < 2/3$ is a weakly insulating one and it reaches a maximum of only 36 k$\Omega/\Box$ at $\nu = 0.40$ at 38 mK.

From the lowest T curve of Fig.1 it is apparent that ρ_{xx} has a fine structure in the vicinity of its maximum close to $B = 1.0$ T. The inset of Fig.1 shows a magnified view of this region. Surprisingly, there are oscillations in ρ_{xx}. The amplitude and period of these oscillations do not depend on the direction of the sweep of the B field, the sweep rate of the field, and the current as long there are no heating effects (for <2 nA). The oscillations are not seen for all voltage probing contacts and we have observed them in three different samples from the same wafer. They are present at different cool downs, though their amplitude and the phase exhibit small variations.

To show the oscillations over the whole B range, we subtracted from ρ_{xx} a background ρ_{xx}^{bg} that is a slowly varying function of B. This background is obtained by fitting ρ_{xx} over about 30 periods of oscillations to polynomials of degree 7. The result is shown in Fig.2. While the oscillations cannot be observed for $B < 0.79$ T, they are present in both the low and the high field insulating phases. Their amplitude reaches a maximum at $B = 1.0$ T in the low field insulating phase, it almost vanishes at $\nu = 1/3$, then it is very large again beyond 1.3 T in the high field insulating phase. The oscillations persist to fields as high as 1.45 T, a value beyond which there are large nonperiodic fluctuations. In a first order approximation the amplitude of the oscillations scales with ρ_{xx}.

In the following we investigate the nature of the observed oscillations. Fig.3 shows the index j labeling the local maxima of ρ_{xx} as a function of B and $\nu = hp/(eB)$. j versus ν is not linear, therefore the oscillations are not of the Shubnikov-de Haas type. Replacing the abscissa with $1/(B - B_{\nu=1/2})$ leads to even stronger nonlinearities (not shown), therefore the oscillations cannot be due to composite Fermions [15]. Since the $\nu = 1/3$ state is known to be spin-polarized, it is unlikely that the oscillations are due to a spin effect. j as a function of B, also shown in Fig.3, is quasi-linear. The oscillations of ρ_{xx} are therefore quasi-periodic in B with the period being the inverse slope of the j versus B curve. The resulting period δB, shown in Fig.4a, increases linearly with B.

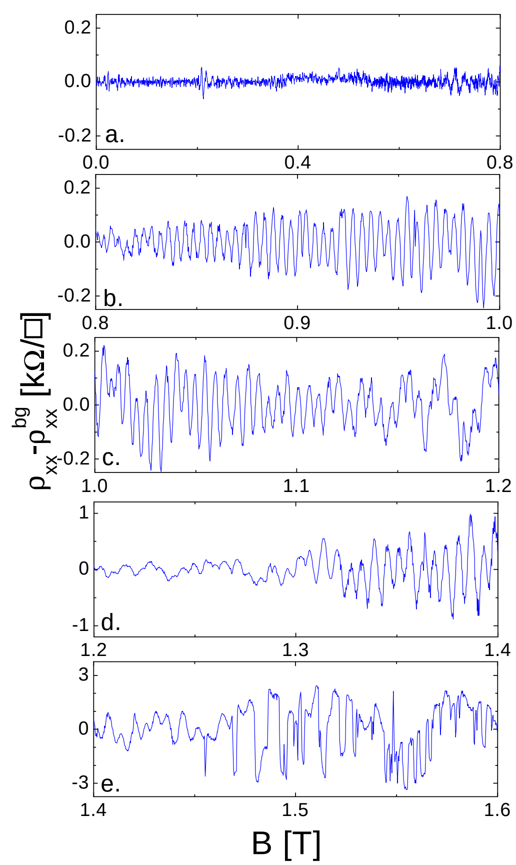

FIG. 2: The dependence of ρ_{xx} on B after the subtraction of a smooth background ρ_{xx}^{bg}. Note the change of scale of the vertical axis for panels d. and e.

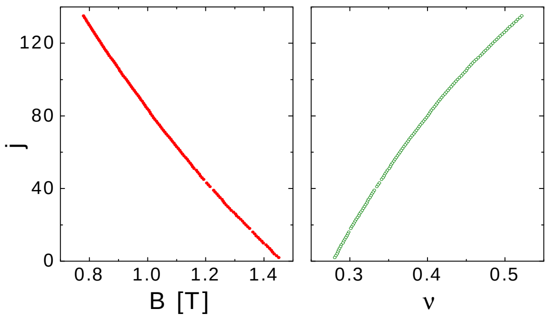

FIG. 3: The dependence on B and ν of the index j of the maxima of the oscillations of ρ_{xx}.

This period is found to be T-independent.

Periodic modulation of the magnetoresistance of the FQH effect can result from two mechanisms. One of them is the Aharonov-Bohm (AB) interference of the electronic wave function between two conductive paths [16]. Due to constructive and destructive interference the resistance is periodic with successive penetration of one quantum of the magnetic flux $\Phi_0 = h/e$ through the area enclosed by the two paths. A typical period of 6 mT measured in our samples corresponds to $(0.83\ \mu\mathrm{m})^2$. Our samples, however, are of the oder of 1 mm and do not have any *intentional* patterning on scale of 1 μm. Inhomogeneities of the order of 1 μm can arise either from the depletion of the 2DH due to defects in the host GaAs/AlGaAs crystal or from an inhomogeneous electronic phase consisting of two interpenetrating phases. A second mechanism for oscillatory magnetoresistance is the periodic transfer of elementary charges between two interpenetrating phases. In the following we will discuss these possibilities.

The AB effect around fixed defects has been previously observed in lithographically etched rings [17, 18, 19], in a micron size Hall bar [20], in singly connected geometries [21, 22], and in particular, it has been demonstrated in hole samples [23, 24]. Depleted regions in our samples due to defects in the host crystal could similarly lead to AB interference. We argue that this scenario is unlikely. First, for the lithographically etched samples in Refs. [17, 18, 22, 23] the AB oscillations are present at filling at least up to $\nu = 2$. Similarly, quasiperiodic resistance fluctuations due to resonant tunneling through states that are magnetically bound to defects have been observed for $\nu \leq 4$ filling in a 2 μm wide Hall bar [20]. We do not observe any of the oscillations for $\nu > 0.52$ and, in particular, near any integer fillings. Second, the period of AB interference in artificially created mesoscopic systems [17, 18, 22, 23] is independent of B. Indeed, in a submicron size square [17], in a quantum antidot electrometer [18], and in a quantum point contact [22] the period of the AB oscillations changes less than 5% over a B range of more than 100 periods. In contrast, the period δB in our sample almost doubles in the 0.8-1.4 T range. Third, it is improbable that growth defects generated in three different samples would roughly be of the same size yielding oscillations of similar period and amplitude. These results therefore suggest that the AB effect around a fixed defect in the host crystal cannot explain our data.

A second possibility for AB interference is when the 2DH system is not homogeneous but it phase separates on the scale of 1 μm into two coexisting phases. Since the oscillations are present in the insulating phases on both sides of $\nu = 1/3$, the $\nu = 1/3$ FQH liquid and a crystalline phase are natural choices for the two phases. In this scenario, in the vicinity of the $\nu = 1/3$ filling there is an intermediate phase which consists of droplets of FQH liquid and patches of crystal. The patches of crystal are localized by the disorder present in the sample and the droplets of correlated FQH liquid, that percolate through the sample, support the AB interference. The intermediate phase is similar to the theoretically predicted $B = 0$ intermediate phase described in the introduction [9, 10, 11, 12] with the FQH liquid replacing the $B = 0$ Fermi liquid. Since increasing r_s results in enhanced LLM that in turn decreases the energy difference between the solid and the FQH liquid [6], it is possible that the extremely large $r_s = 30$ of our sample causes vanishingly small energy difference between the two phases. Under such conditions both phases are equally favored and the ground state is an intermediate phase as a consequence of the competition between the two phases. From an experimental viewpoint, such a situation is plausible because,

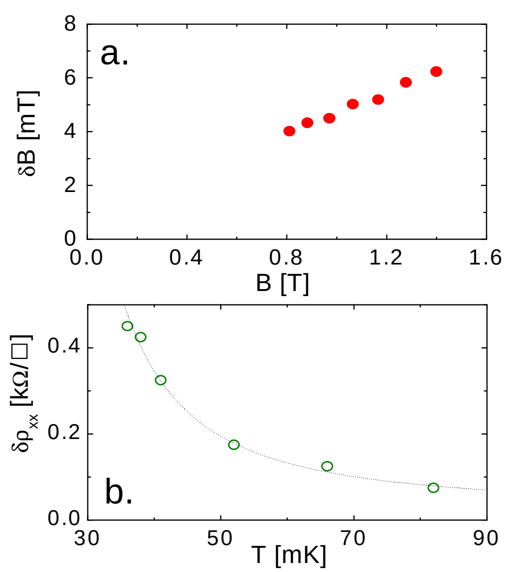

FIG. 4: The period δB of the oscillations of the longitudinal resistivity as a function of B (panel a.) and the amplitude of the oscillations $\delta\rho_{xx}$ at $B = 1$ T as a function of T (panel b.). The dotted line is a guide to the eye.

due to the almost T-independent ρ_{xx} at $\nu = 1/3$, the FQH liquid is extremely fragile.

Details of our data, in this interpretation, are determined by the delicate balance between the coexisting phases. The oscillations of ρ_{xx} are quite sharp with a well defined period. This is most likely because the AB patches have a very narrow size distribution, perhaps due to surface tension effects. However, we cannot discard the possibility that only one patch is dominant in determining the period. The linearly increasing δB with B we measure is consistent with the liquid phase being enclosed by the interfering paths. Indeed, a droplet of N_{liq} holes and of area A_{liq} must shrink with increasing B since the filling factor the liquid $\nu = N_{liq}\Phi_0/(A_{liq}B)$ remains constant. A decreasing area with increasing B results in an increasing period via the AB condition $A_{liq}\delta B = \Phi_0$. Furthermore, combining the last two equations we obtain $\delta B = \nu B/N_{liq}$. The linearly increasing period with B agrees with the data of Fig.4a and yields $N_{liq} = 66$. The T-independence of δB can be explained by the rapid destruction with increasing T of the phase coherence while droplets have not significantly changed with T. Lastly we note, that AB interference over distances of 1 μm is possible in our sample because the AB effect has been observed in samples with linear size close to the elastic scattering length [19] and this length in our sample is 0.59 μm.

The alternative route that leads to periodic modulation of ρ_{xx} is the charge transfer between the two electronic phases earlier described. We argued that the size of a liquid droplet shrinks with increasing B. At a certain value of B it could become more favorable for the droplet to exchange an elementary charge with a patch of solid rather than shrink. As a result, the magnetic flux of the droplet changes by $3\Phi_0$ and the droplet relaxes size after the charge transfer. With further increase of B, the size of the droplet shrinks again and the described process is periodic with B. It is interesting to point out that for this process, as opposed to the AB effect, it is possible that the period δB of the charge transfer is independent of the size of the droplets and consequently the oscillations are not smeared out by averaging. We wish to point out that the charge transfer process between the two phases described here and the charging of isolated islands, known as the Coulomb blockade [25], are quite different. While both processes involve charge transfer, the former one is between the coexisting compressible solid and incompressible correlated liquid phases in 2D, the latter one is in between two charge reservoirs through the 0D states of the quantum dot between the reservoirs.

In conclusion, we have observed quasiperiodic modulation of the Shubnikov-de Haas magnetoresistance in very low density and large r_s 2DH samples. These oscillations are present in the insulating regions on both sides of the $\nu = 1/3$ FQH state. We argue, that due to the large LLM the 2DH gas most likely is not homogeneous, instead it phase separates into droplets of FQH liquid and patches of solid. Assuming that the oscillations observed are the manifestation of the AB effect, the size of the patches around which the interference occurs is of the order of 1 μm. Charge transfer between the liquid and solid phases might also provide a viable explanation.

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